FOURIER ANALYSIS OF EXPERIMENTAL FINITE-AMPLITUDE STANDING WAVES

James Richard Winn

United States
Naval Postgraduate School

THESIS

FOURIER ANALYSIS OF EXPERIMENTAL
FINITE-AMPLITUDE STANDING WAVES

by

James R. Winn

Thesis Advisor: J. V. Sanders

June 1971

Approved for public release; distribution unlimited.

T139961

Fourier Analysis of Experimental Finite-amplitude Standing Waves

by

James Richard Winn
Lieutenant, United States Navy
B.S.E.E., University of Washington, 1964

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN PHYSICS

from the

NAVAL POSTGRADUATE SCHOOL
June 1971

ABSTRACT

Finite-amplitude standing waves in air at ambient conditions contained in a rigid-walled cylindrical tube with a large length-to-diameter ratio were experimentally investigated. The pressure waveform at the end of the tube was digitized and Fourier analyzed on an IBM 360 digital computer. Amplitudes and phases were obtained for all harmonics with amplitudes greater than 1% of the fundamental for strength parameters from 0.25 to 1.00 and for frequency parameters from -0.8 to 2.0. The strength and frequency parameters are defined as MbQ and $2\Delta f/\Delta f_{\frac{1}{2}}$ respectively, where M is the Mach number of fundamental, b the nonlinearity parameter, Q the quality factor of the resonator, Δf the frequency away from fundamental resonance, and $\Delta f_{\frac{1}{2}}$ the band width at the half-power points. When these results are compared to the theoretical model of Coppens and Sanders, it is seen that while the theory accurately predicts the magnitude and shape of the harmonic content, it consistently underestimates the frequency at which each harmonic peaks. In addition, the theory fails to predict, except qualitatively, the phase angles.

TABLE OF CONTENTS

I. INTRODUCTION ---------- 5

II. EXPERIMENTAL CONSIDERATIONS ---------- 9

A. APPARATUS ---------- 9

B. MICROPHONE CALIBRATION ---------- 10

C. MICROPHONE OUTPUT AND STRENGTH PARAMETER ----- 12

D. ATTENUATION CONSTANT ---------- 12

E. FREQUENCY PARAMETER ---------- 13

III. COMPUTER ANALYSIS ---------- 14

A. SAMPLE RATE ---------- 14

B. THE DIGITAL COMPUTER PROGRAM ---------- 15

C. THE ANALOG TO DIGITAL CONVERSION ---------- 16

D. SYSTEM TEST ---------- 18

IV. PROCEDURES ---------- 19

A. PRERUN PROCEDURES ---------- 19

B. DATA TAKING PROCEDURES ---------- 20

V. RESULTS ---------- 21

APPENDIX A: A-D PROGRAM PARAMETERS AND OPTIONS -------- 23

APPENDIX B: FIGURES AND PLOTS ---------- 26

COMPUTER PROGRAMS ---------- 39

BIBLIOGRAPHY ---------- 50

INITIAL DISTRIBUTION LIST ---------- 51

FORM DD 1473 ---------- 52

LIST OF FIGURES

1. Apparatus Block Diagram ---------- 26
2. PI 6200 Dynamic Range ---------- 27
3. Analog Patch Board ---------- 28
4. Logic Patch Board ---------- 29
5. Test Signal Analysis ---------- 30
6. Point Scatter ---------- 31
7. Harmonic Amplitudes SP = 0.25 ---------- 32
8. Harmonic Amplitudes SP = 0.50 ---------- 33
9. Phase Plot SP = 0.50 ---------- 34
10. Harmonic Amplitudes SP = 0.75 ---------- 35
11. Phase Plot SP = 0.75 ---------- 36
12. Harmonic Amplitudes SP = 1.00 ---------- 37
13. Phase Plot SP = 1.00 ---------- 38

I. INTRODUCTION

Coppens and Sanders [1,2] have developed a one-dimensional, nonlinear wave equation with dissipative terms corresponding to those encountered in a rigid-walled closed tube with a large length-to-diameter ratio. An attenuation constant of the form

$$\alpha_n = \alpha_1/\sqrt{n}$$

is assumed, where α_n is the absorption coefficient associated with the frequency $n\omega$ which characterizes the wall losses, R is the radius of the tube and L is the length of the tube. With this additional loss mechanism the wave equation takes the form

$$\sum_{n=1}^{\infty} \left(\frac{\partial^2}{\partial x^2} - \frac{1}{C_o^2} \frac{\partial^2}{\partial t^2} + D_n \right) U_n = b \frac{\partial^2}{\partial x \partial t} \left(\frac{\partial \xi}{\partial x} \right)^2 ,$$

where

$$b = (\gamma+1)/2 = (C_p/C_v+1)/2,$$

$$D_n = \delta_1 \left(\frac{1}{\omega n^{3/2}} \frac{\partial^3}{\partial x^2 \partial t} - \frac{1}{n^{1/2}} \frac{\partial^2}{\partial x^2} \right),$$

$$\delta_1 = \frac{2}{R} \left(\frac{\nu}{2\omega} \right)^{1/2} \left[1 + \frac{\gamma-1}{(Pr)^{1/2}} \right],$$

$\gamma = C_p/C_v$ the ratio of specific heats,

ν = kinematic viscosity,

Pr = Prandtl number,

ω = angular frequency of the fundamental,

n = harmonic number,

C_o = the thermodynamic speed of sound,

α_1 = absorption coefficient for the lowest frequency

and

$$U = \text{particle velocity} = \frac{\partial \xi}{\partial t} + \sum_n U_n .$$

To arrive at the above equation it was necessary to make the simplifying assumptions that the wall losses were much greater than the bulk losses and that the Mach number

$$M = P_1/\rho_o C_o^2$$

is much less than unity. P_1 is the peak value of the fundamental of the pressure at the rigid end of the tube.

A Fourier series solution of the form

$$\frac{P(x_1 t)}{\rho_o C_o^2} = M \sum_{n=1}^{\infty} R(n) \operatorname{Cos}\left[n\pi\left(1-\frac{x}{L}\right)\right] \operatorname{Sin}(n\omega t+\phi n)$$

is assumed with the tube excited with a pressure distribution given by

$$P_1(x_1 t) = M\rho_o C_o^2 \operatorname{Cos}\pi(1-x/L)\operatorname{Sin}\omega t.$$

When this solution was substituted directly into the nonlinear wave equation, the following set of algebraic equations resulted:

$$H_n\left[(\operatorname{Cos}\theta_n)S_n - (\operatorname{Sin}\theta_n)C_n\right]$$

$$= \frac{n}{2\ell_s}\left\{\frac{1}{2}\sum_{j=1}^{n-1}(S_{n-j}C_j+C_{n-j}S_j) - \sum_{j=1}^{\infty}(S_{n+j}C_j-S_{n+j}S_j)\right\}$$

and

$$H_n\left[(\mathrm{Cos}\theta_n)C_n + (\mathrm{Sin}\theta_n)S_n\right]$$

$$= \frac{n}{2\ell_s}\left\{\frac{1}{2}\sum_{j=1}^{n-1}(C_{n-j}C_j - S_{n-j}S_j)\right.$$

$$\left. - \sum_{j=1}^{\infty}(C_{n+j}C_j + S_{n+j}S_j)\right\},$$

where

$S_n = R_n \mathrm{Sin}\ \phi_n$, $C_n = R_n\ \mathrm{Cos}\ \phi_n$,

$\ell_s = 2/SP$,

$$\theta_n = \mathrm{Tan}^{-1}\left[\frac{1 - n^{-\frac{1}{2}} - 2\Delta\omega/\omega_r\delta_1}{n^{-\frac{1}{2}}\mathrm{tn}\alpha_2/\alpha_1}\right]$$

$$= \mathrm{Tan}^{-1}[A/B]_1$$

$H_n = (A^2+B^2)^{\frac{1}{2}}$,

α_2 = infinitesimal amplitude absorption coefficient in free space,

ω_r = angular frequency at resonance,

SP = strength parameter

$SP = Mbk/2_{\ 1} = P_1 bk/(2\rho_o C_o{}^2\alpha_1)$

k = wave number

and

$\Delta\omega = \omega - \omega_r$.

These equations were then programmed for computer solution. For given values of $\Delta\omega$ and SP, the computer calculated values of P_n/P_1 and θ_n. At present, solutions have been found for strength parameters up to 0.75.

Previous investigations in this area have been carried out by Sanders [1,2] and Beech [3]. Both investigators examined the harmonic content of the pressure waveform at the rigid end of the tube near resonance conditions. Sanders employed a wave analyzer to obtain the frequency response for the first four overtones. Good agreement with theory was found but no phase information was obtained. Beech used photographic and graphical techniques to provide numerical analysis of pressure waveforms near resonance. Phase information, however, was obtained only for cases at resonance. Again good agreement with theory was obtained for cases approaching the onset of shock.

The present investigation examines both the harmonic content and phase relationships for strength parameters as high as 0.75. Again numerical methods were employed. Whereas the graphical techniques of Beech were used to generate 64 data equally spaced throughout the pressure wave form, the technique in this investigation employed analog-to-digital conversion by computer to provide better than 1000 data to represent the pressure waveform. With the pressure waveform digitized to such an extent, it was possible to obtain amplitude and phase information for all harmonics with amplitudes greater than one percent of the fundamental.

II. EXPERIMENTAL CONSIDERATIONS

A. APPARATUS

A block diagram of the experimental system used in this investigation is shown in Figure 1. Finite-amplitude standing waves were generated in air at ambient conditions contained within a tube six-feet long with an inner diameter of 2.250 in. and a wall thickness of 1.125 in. The air was excited at one end by a piston which was driven by an M-B Electronics Model EA 1500 exciter capable of a maximum no-load acceleration of 124g. The EA 1500 was driven by two M-B electronics Model 2120MB power amplifiers operating in parallel. The maximum attainable acceleration with the weight of the piston as load was about 50g. The frequency and power level were controlled by a General Radio Type 1161-AGC coherent decade frequency synthesizer. With this synthesizer it was possible to select frequency to better than 0.001 cycles/sec. (Monitoring the frequency with a Hewlett-Packard Model 521C frequency counter showed the frequency stability to be better than one part in 10 million.) The acceleration of the piston was determined by measuring the output an Endeveco Model 2215 accelerometer implanted within the piston. When the piston was withdrawn from the tube and driven in free air at the approximate experimental frequency and acceleration, the harmonic distortion was measured to be less than 0.3 percent. The other end of the

tube was capped with a thick plate which was securely bolted to the tube. The sound pressure level at the rigid end of the tube was detected with a 1/4-in. diameter Bruel and Kjaer Type 4136 condenser microphone mounted in the cap so that its diaphragm was flush with the end of the tube. The microphone response was flat to within $\pm$ 0.5 dB from 80 Hz to 20 kHz. The outputs of the microphone and accelerometer were monitored with Hewlett-Packard 400D vacuum-tube voltmeters. The microphone output also went to a Hewlett-Packard Model 302A wave analyzer so that the first two overtones could be monitored. The microphone output was recorded by a PI 6200 General Purpose Portable Instrumentation Tape Recorder. Recordings were made in the FM mode at a tape speed of 37.5 in/s so that the frequency response of the tape recorder was $\pm$ 1 dB from DC to 10 kHz. Although the signal was recorded at 37.5 in/s it was necessary when digitizing the signal to play back at a speed of 3.75 in/s. To insure that this change in tape speeds did not alter the recorded frequencies, a test signal was recorded at the higher speed and then played back at the slow speed. The two signals were observed on a dual trace oscilliscope where it was observed that the frequency of the test signal was 10.0 times that of the signal played back at 3.75 in. per second with no discernable drift between the two signals.

B. MICROPHONE CALIBRATION

Investigation of the standing waves at various strength parameters requires an absolute calibration of the microphone

system. The microphone system is defined here as the microphone, preamplifier and the equipment loaded onto the output of the preamplifier. The system sensitivity is defined as

$$S_m = V_m/P$$

where V_m is the peak voltage output of the preamplifier and P is the peak pressure at the microphone. Two methods were employed to determine S_m. The first and simplest used a Bruel and Kjaer Model 4220 pistonphone which produces a known sound pressure level at 250 Hz. The sensitivity was found to be $S_m = (-77.1 \pm 0.2)$dB re 1 volt/μbar, where the uncertainty is that inherent in the pistonphone specifications. The second method makes use of theoretical predictions by Coppens for small strength parameters as verified by Beech [3]. Coppens shows that at resonance the ratio of the peak pressure of the second harmonic to the square of the peak pressure of the fundamental is given by

$$P_2/P_1^2 = (\sqrt{2}\ \omega\beta)/(8\rho_o C_o^3 \alpha).$$

When the definition of sensitivity is substituted into the above equation the result is

$$S_m = (\beta\omega V_1^2)/(4\sqrt{2}\ \rho_o C_o^3 \alpha V_2).$$

S_m was then found by exciting the tube at resonance and measuring the fundamental and second-harmonic voltages. By this method $S_m = (-77.2 \pm 0.3)$dB re 1 volt/μbar where the uncertainty is due largely to the error in determining the attenuation constant.

C. MICROPHONE OUTPUT AND STRENGTH PARAMETER

In this investigation, where the pressure waveform was to be analyzed at various strength parameters, it was necessary to find a relationship between the strength parameter and the observable quantities. Using the equations

$$S_m = SPL + 21 \log\left(\frac{\nu}{.775}\right) + 72.0,$$

$$M = \frac{P_1}{\rho_o C_o^2} = \frac{P_1}{P_o} - \frac{P_o}{\rho_o C_o^2} = SPL - 197.0,$$

and

$$M = \frac{SP(2\alpha/K)}{b},$$

one can show that the rms value of the fundamental of the microphone output (v) is related to strength parameter and the attenuation constant by

$$v = 136.0\, \alpha \cdot SP.$$

The constant 136.0 is relatively insensitive to small temperature variations about room temperature.

D. ATTENUATION CONSTANT

The attenuation constant for infinitesimal amplitudes has been shown by Beech to be

$$\alpha_1 = \left(\frac{\pi}{C_o}\right) \Delta f,$$

where Δf is the frequency difference between the half power points on the resonance curve (taken for constant acceleration amplitude of the piston).

E. FREQUENCY PARAMETER

The frequency parameter is defined by

$$FP = 2\Delta\omega/\omega_r\delta_1,$$

where

$$\Delta\omega = \omega - \omega_r$$

and

$$\delta_1 = 2\alpha_1 C_o/\omega_r.$$

This frequency parameter is related to the experimental frequency increment (Δf_{ex}) by

$$\Delta f_{ex} = \Delta f \cdot FP/2,$$

where Δf is the frequency difference between the half power points of the infinitesimal resonance curve as used in calculating α_1 in this investigation Δf was found to be $1.15 \pm 0.01 H_3$ so that

$$\Delta f_{ex} = 0.58\ FP.$$

III. COMPUTER ANALYSIS

A. SAMPLE RATE

Many computer programs exist which, when supplied with data points defining a periodic waveform, will give the Fourier coefficients. The first consideration, generally, is the number of data required per cycle. Theoretically this number should be at least twice the number of harmonics desired. However, the question of accuracy of the computer predictions of harmonic amplitudes arises immediately. As might be expected, the accuracy of the harmonics determined tails off faster as fewer samples per cycle are used. This then leads to the problem of first determining how many significant harmonics are desired. For finite-amplitude standing waves of large strength parameter the waveform qualitatively approaches a function whose harmonics content falls off inversely with harmonic number. If such a waveform is passed through amplifiers and storage devices before being analyzed, harmonics below a given amplitude will be lost in the inherent noise. The device in this investigation which was most seriously restrictive in this respect was the PI 6200 FM tape recorder. It was found that the dynamic range of this instrument was about 42 db which restricted the investigation to harmonics with amplitudes greater than about one percent of the fundamental. For a periodic ramp function this restriction occurs at about the 30th harmonic.

Determination of the number of samples per cycle to be used was based on the arbitrary criterion that the error in the 30th harmonic be less than 0.1 percent for an ideal ramp function. Applying several computer algorithms for determining Fourier coefficients to an ideal ramp function one finds that 1000 samples per cycle are required for the above accuracy.

B. THE DIGITAL-COMPUTER PROGRAM

The primary function of this program was to generate normalized Fourier coefficients for a periodic function given digitized data on a seven-track tape. Secondary to this, the program changed the form of the coefficients to $A(n)\ \mathrm{Sin}(N\omega t + \phi(n)$ and computed $A(n)/A(1)$ for each harmonic. Optional functions provided by the program were the averaging of several periods of data to reduce the affects of random noise. An optional plot of the input data was available along with points reconstructed from the calculated Fourier coefficients. This plot provided a visual check on the input data and the computed coefficients.

The digitized data provided by the SDS 9300 were written on seven-track tape. However, the binary representation of numbers on the seven-track tape differs from those on the standard nine-track tape used by the IBM 360 system. To accomodate the seven-track tape, a conversion program (subroutine FORM) was used to convert the data. The converted data were not floating point but integers and required further conversion with the use of a scaling factor.

Prime consideration was given to the types of algorithms commonly used in generating Fourier coefficients. Two of the more widely used methods are the Cooley-Tukey [5] Fast Fourier transform and the recursive technique of Goertzel [4]. Both methods were tested for accuracy in predicting the coefficients of known waveforms. The two methods were found to be equal. One advantage of the Cooey-Tukey method is its minimal use of computer time. Its computation time is about an order of magnitude less than that required by the Goertzel method. However, when this time saving is compared with the overall required computer time for analysis the advantage diminishes. The final consideration and, in the end the most important, was the flexibility in using data. The Cooley-Tukey method required an integer power-of-two number of points. To be able to satisfy this condition along with the requirement for 1000 or more samples per cycle complicated the digitizing process. The Goertzel method required only an odd number of samples and for this reason was used in the computer program.

C. THE ANALOG TO DIGITAL CONVERSION (A-D)

The conversion of the analog data was accomplished with the use of a hybrid computer consisting of the SDS 9300 high-speed digital computer and the Ci 5000 general-purpose analog computer. Use of the system for A-D conversion requires a FORTRAN program for the SDS 9300 and properly constructed analog and logical patch boards for the Ci 5000. In addition, several peripheral equipments are required.

These are the card reader, magnetic tape transport, line printer and, if desired, a pen recorder.

Aside from the question of sampling, which was determined earlier, the important question in the A-D conversion is accuracy. The clock in the computer is accurate to one part in 100 million, well within any accuracy requirements. The A-D converter is designed to accept signals between $\pm$ 100 volts and divide this interval into 16,384 parts providing a resolution of 12.2 mV. For a properly amplified analog signal, the dynamic range of the A-D converter is much greater than the PI 6200 tape recorder.

The analog patch board (Figure 3), as used for A-d conversion, served to amplify the analog signal prior to conversion and distributed the signal to the converter and oscilliscope. Additionally, a patch was provided linking the Digital-to-Analog converter with a pen recorder. This additional function is explained in detail in the procedures section.

The logic patch board (Figure 4), had three functions. The first provided a sampling frequency (10,000 Hz) to the A-D converter. This frequency represents the approximate maximum sampling rate allowed. Since the approximate resonant frequency of the tube was 94 Hz it was necessary to play back signals from the PI 6200 at one tenth the recorded speeds to acquire the desired number of samples per cycle. The second function provided a triggering voltage through an external switch (DS-1) which was used to start the data

conversion process. Associated with this function is an externally controlled delay (DF00) which insured that the triggering voltage remained on long enough for one set of data (one record) to be written on the seven-track tape. The last function provided another triggering voltage through an external switch (DS-2). When the last record was to be written on tape switch DS-2 was turned on while switch DS-2 was triggered.

D. SYSTEM TEST

Prior to analyzing experimental data, it was necessary to test the entire system process of A-D conversion and computer analysis. The results of this test for a ramp function is shown in Figure 5.

IV. PROCEDURES

A. PRERUN PROCEDURES

Beech pointed out that the resonant frequency of the tube changed by 0.16 Hz for each degree centigrade of temperature change. To minimize this affect, all data gathering runs were made during the evening hours when the room temperature remained relatively constant for several hours. Typical resonant frequency variations during these hours were of the order of 0.01 Hz per hour. Several hours prior to taking data the equipment was turned on and allowed to stabilize. During this warmup period, the PI 6200 tape recorder was calibrated to insure that the FM system was properly aligned and to insure that the signals being recorded were not overdriving the tape recorder preamplifier and thereby introducing unwanted signal distortion. Next, the alignment of the piston in the free end of the tube was checked by observing the output of the accelerometer on an oscilloscope and measuring, with a wave analyzer, the second- and third-harmonic content. If necessary, the harmonic content could be reduced by carefully adjusting the alignment of the piston so that the distortion from any harmonic was less than 2 percent. To minimize leakage of sound from the tube, the piston was fitted with an "O" ring and lubricated. The harmonic distortion introduced by the piston was sensitive to the type of lubricant

used. It was found that a light turbine oil minimized the distortion while providing an adequate seal.

Just prior to taking each set of data, it was necessary to determine the resonant frequency and the attenuation constant. For this measurement the piston was excited at a constant value of acceleration low enough so that the strength parameter at resonance was less than 0.03. From the frequency difference between the half power points, the attenuation constant was determined. The resonance frequency was taken to lie half way between the half power points.

B. DATA TAKING PROCEDURE

Corresponding to the desired strength parameter was a given value of the pressure fundamental as shown earlier. With the piston excitation set to the proper level to keep the pressure fundamental constant, data were recorded at 0.1 Hz intervals for twenty frequencies from 0.6 Hz below resonance to 1.3 Hz above. At each frequency, the signals from the microphone and accelerometer were recorded on the PI 6200 at high speed (37.5 in/s) for about 10 seconds (30 ft.), and the second-harmonic amplitude of the pressure was noted to be later compared with the computer analysis. Since the taking of an entire set of data at one strength parameter required from 30 minutes to an hour, at the end of the run it was necessary to check the resonant frequency and attenuation constant to insure that the variation in resonant frequency was substantially less than one frequency interval (0.1 Hz) and that the change in attenuation constant was less than one percent.

The theoretical predictions (8) are compared with the experimental results in Figures 6 through 13 for each value of strength parameter, plots are shown of the harmonic amplitude vs. frequency parameter and of the phase difference between consecutive harmonics vs. inverse harmonic number. Figure 6 shows the actual data obtained for three different experimental runs. The degree of scatter is a demonstration of the excellent reproducibility of the results. Both experimental and theoretical results are limited to harmonics with amplitude greater than 1% of the fundamental.

In comparing the experimental values of the harmonic amplitudes with the theoretical predictions for a strength parameter of 0.25 it is seen that the agreement is fairly good but that there does seem to be a slight systemat c difference. The corresponding curves for higher strength parameters display this difference to a more marked degree. It is seen that the experimental results peak at about the predicted values of $P_{(n)}/P_{(1)}$ and that the shape of the curve for each harmonic is about as predicted. However, the experimental results peak at a value of frequency parameter significantly greater than predicted and this difference increases with harmonic number. It is interesting to note that at the frequency of maximum distortion of the pressure waveform (at approximately FP = 0.5) theory accurately predicts the harmonic amplitudes.

The comparison between the experimental and theoretical phase angles displays an even greater discrepancy. While

values of $\phi_n - \phi_{n-1}$ do seem to be linearly related to 1/n, the values for the second harmonic are greatly different and the slopes of the experimental curves are significantly greater than predicted.

In conclusion, it appears that while the present theoretical model is able to predict the magnitude and shape of the harmonic content of the distorted waveform, it consistently underestimates the frequency at which each harmonic peaks. This underestimation increases with harmonic number and strength parameter. In addition, it fails to predict, except qualitatively, the phase relations in the distorted wave.

APPENDIX A

THE A-D PROGRAM PARAMETERS AND OPTIONS

The purpose of this program was to convert up to four channels of analog data into a series of digital points on seven-track magnetic tape. The program had several input parameters which had to be provided to the computer via the teleprinter after the FORTRAN program had been read into the system.

NSAMP (input 1.) was an integer which corresponded to the number of data or samples to be taken from each channel. For this investigation a sampling rate of 10 kHz was used and NSAMP was chosen to span one cycle of the input waveform.

NCHAN (input 2.) was an integer which specified the number of channels of analog data being converted.

NREC (input 2.) specified how many records were to be written on tape each time sampling was initiated. A record was defined as the data set corresponding to the product of NCHAN and NSAMP. Because of the high sampling rate used it was necessary to set this value to 1.

ITAPE (input 4.) designated which magnetic-tape transport held the seven-track tape. The integer used here had to correspond that selected on the "unit select" switch on the particular tape unit used.

NDEL (input 5.) determined how rapidly the data on the seven-track tape was read back when using program option 7.

An example of the input parameters as typed on the teleprinter might be

NREC = 1, NSAMP = 1000, NCHAN = 3, ITAPE = 1,
NDEL = 20* (carriage return).

The control symbol * indicated to the computer that the input parameters had been set. Care was taken when choosing NSAMP and NCHAN to insure that their product did not exceed the first dimension of IBUF found in the first FORTRAN program statement.

When the parameter list had been given the teleprinter responded with

"OPTION = (I1)".

The computer was then given a one-digit number corresponding to the list of available options.

RESTART (option 1.) was used whenever any one or all of the input parameters was to be changed.

GO (option 2.) was used when analog to digital conversion was to be done. Upon receiving this option the computer awaited the initiating trigger from switch DS-1 to start the actual conversion process. Each trigger from DS-1 caused one record of data to be written on tape. When a sufficient number of records were written, DS-1 was triggered with DS-2 in the "up" position. This caused the last record to be written followed by a teleprinter response

"OPTION = (I1)".

END OF FILE (option 3.) was used to put a mark on the tape to separate or isolate groups of records. Groups of records separated by END OF FILE marks are called files.

SKIPFILES (option 5.) were used when files already on tape were to be skipped over. When used, a four-digit number was given the computer to specify the number of files to be skipped.

LIST ONE RECORD (option 6.) was used in reading data from the seven-track tape. Use of this option caused data written on tape to be written on the page printer after having specified the number of data to print.

PLOT ONE RECORD (option 7.), when called, caused one record to be read from the tape, converted to an analog signal, and fed to terminals T420 through T423 on the analog board (corresponding to channels 1 through 4). The signal could then be monitored on various recording devices. Because of the short duration of the signal it was best displayed on the available pen recorder whose input terminals are found on the analog board (Figure 3). The time base of the signal returned from the tape could be lengthened or shortened by varying the value of the input parameter NDEL.

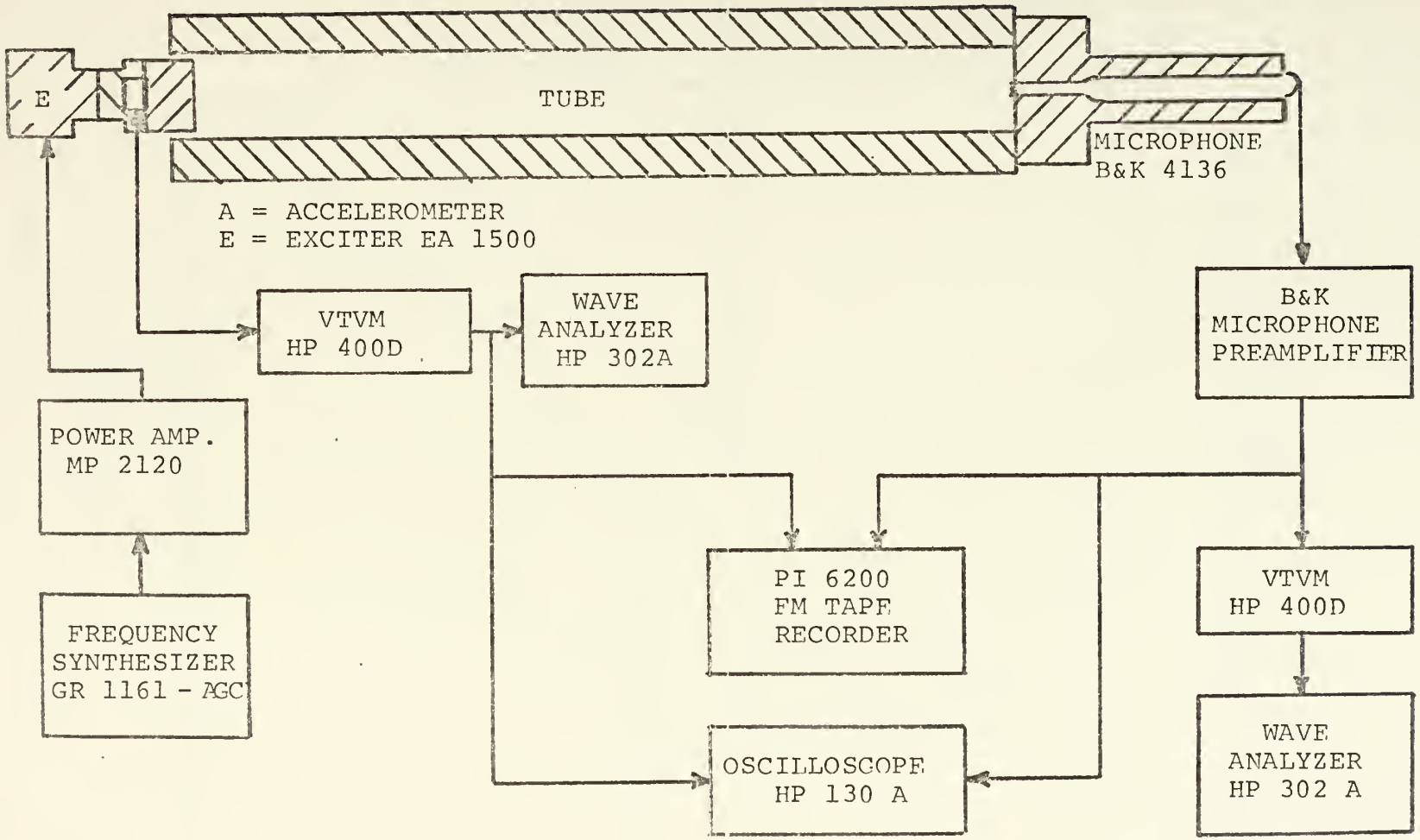


Figure 1. Apparatus.

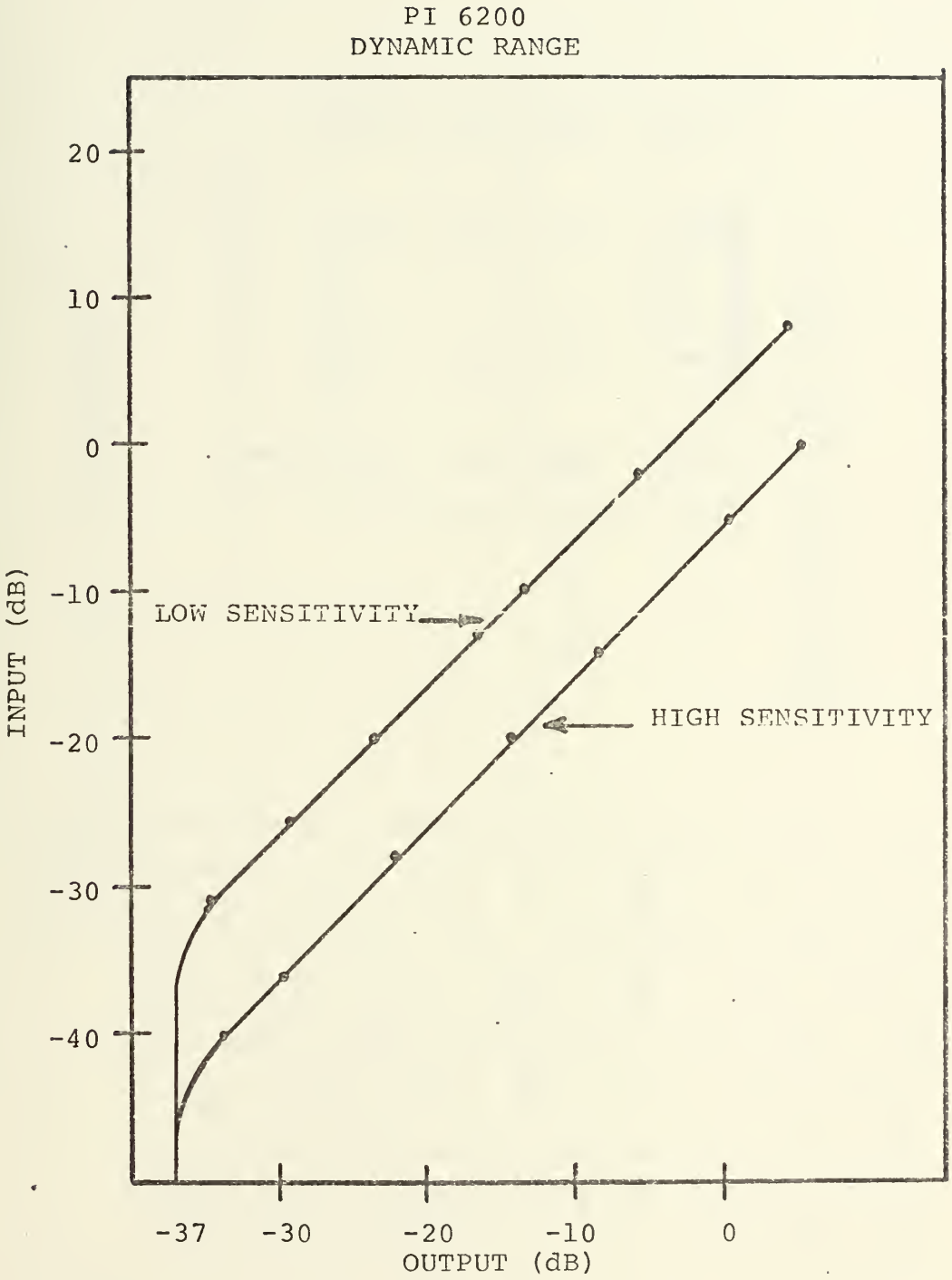


Figure 2. PI 6200 Dynamic Range.

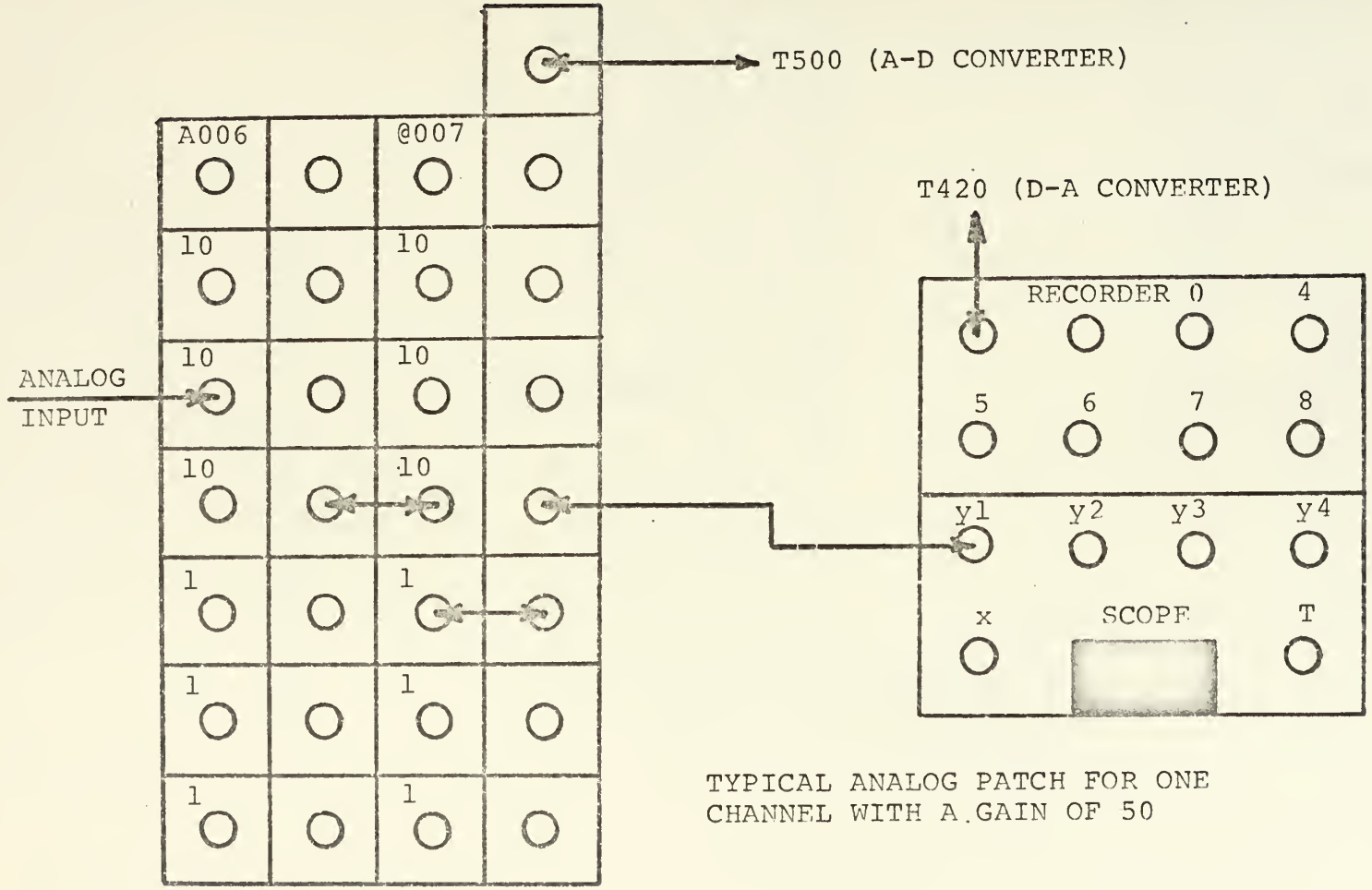


Figure 3. Analog Patch Board.

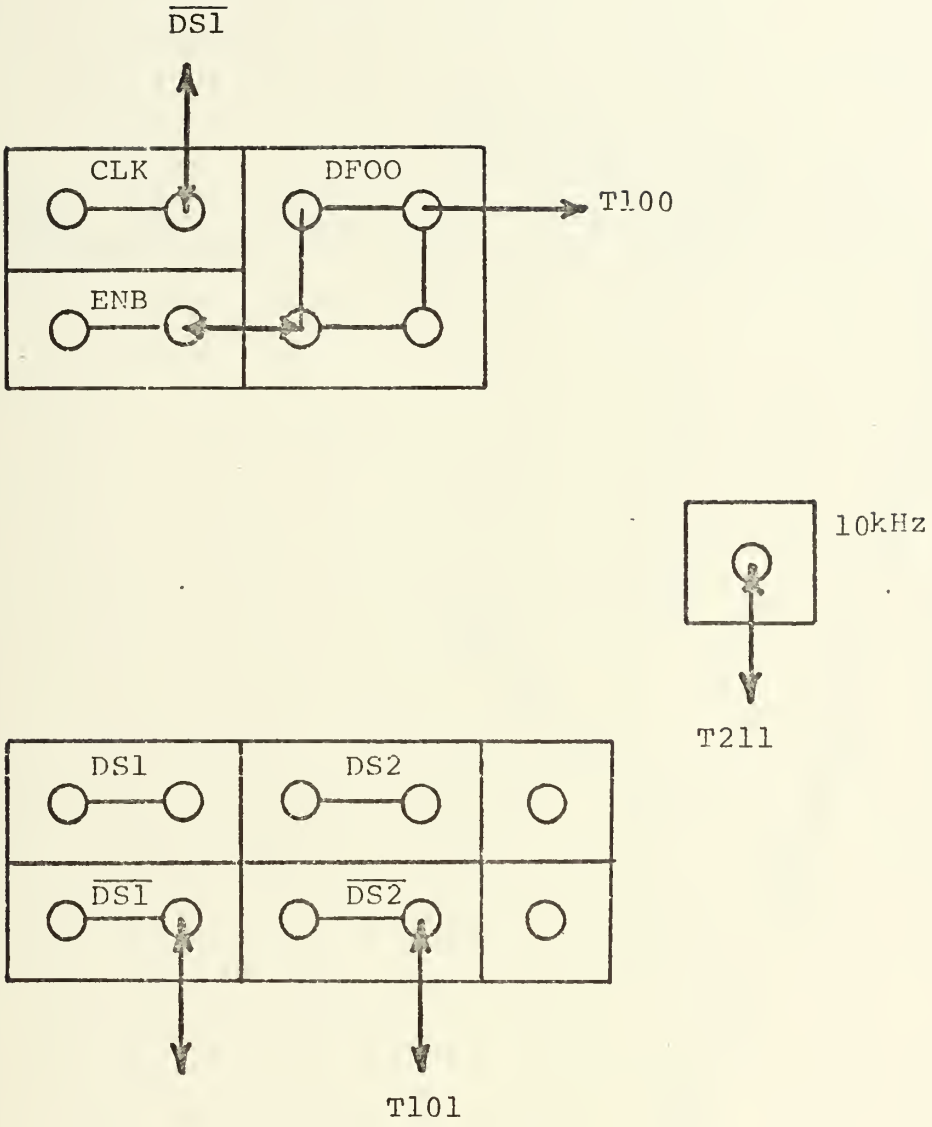


Figure 4. Logic Patch Board.

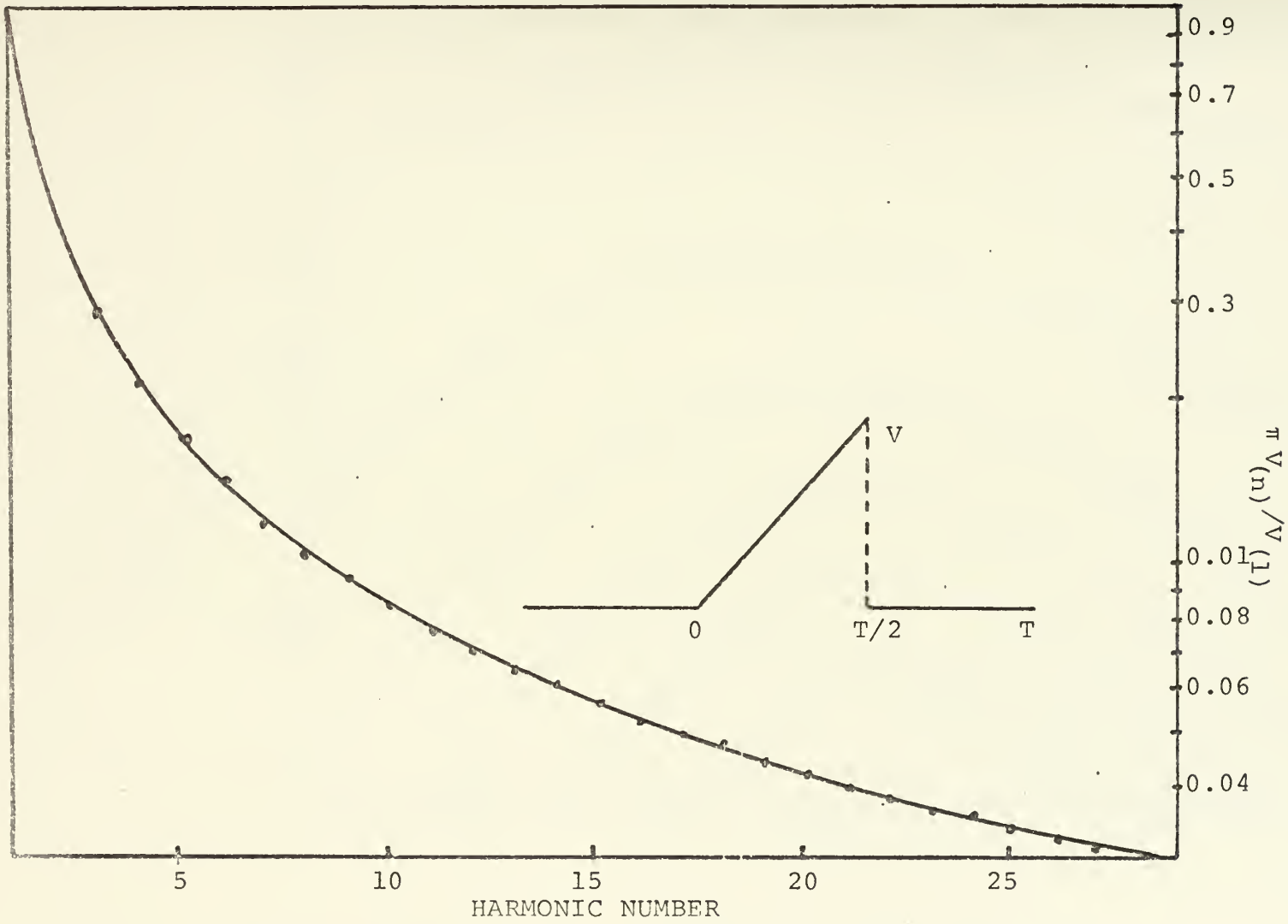


Figure 5. Test Signal Analysis.

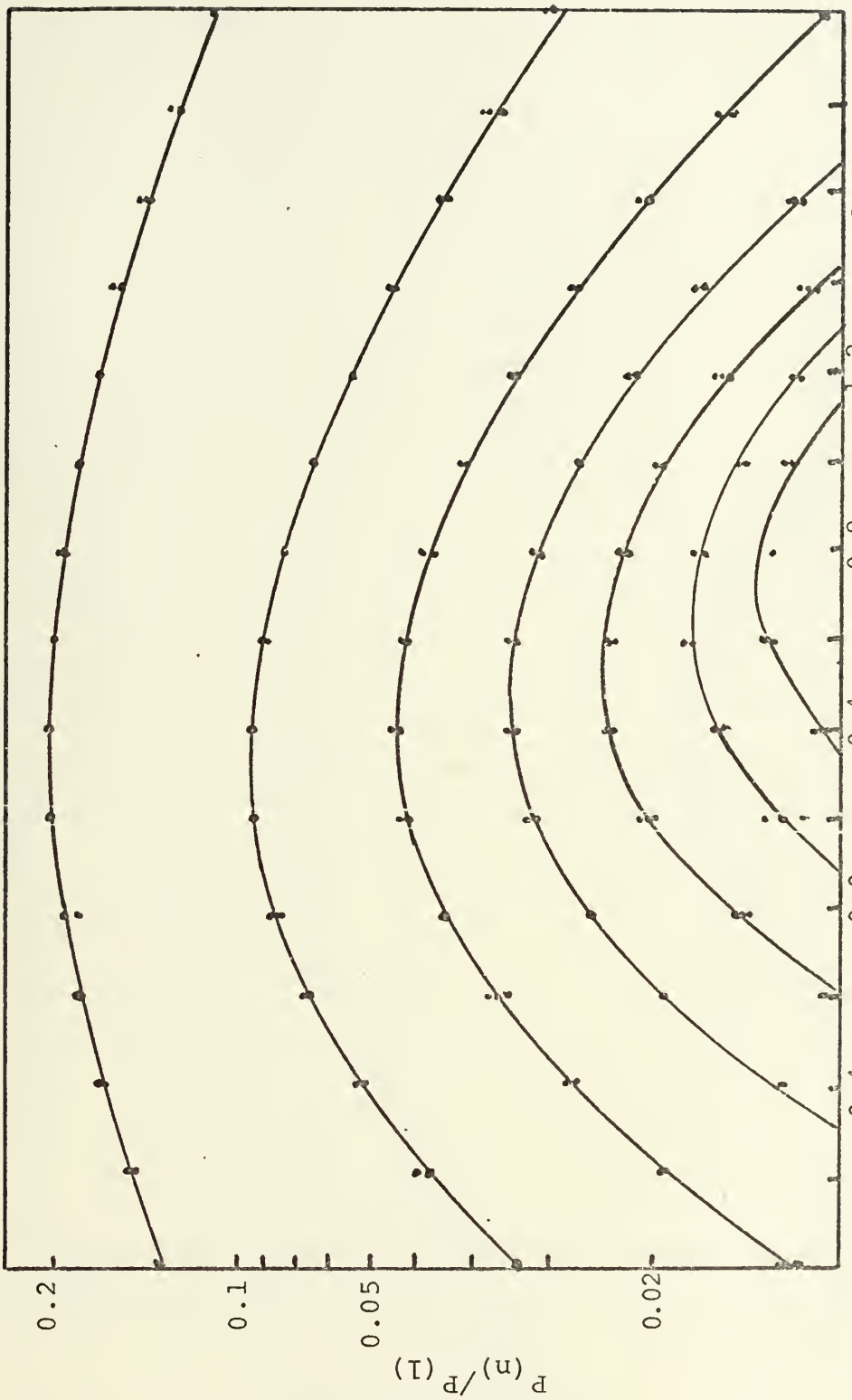


Figure 6. Point Scatter.

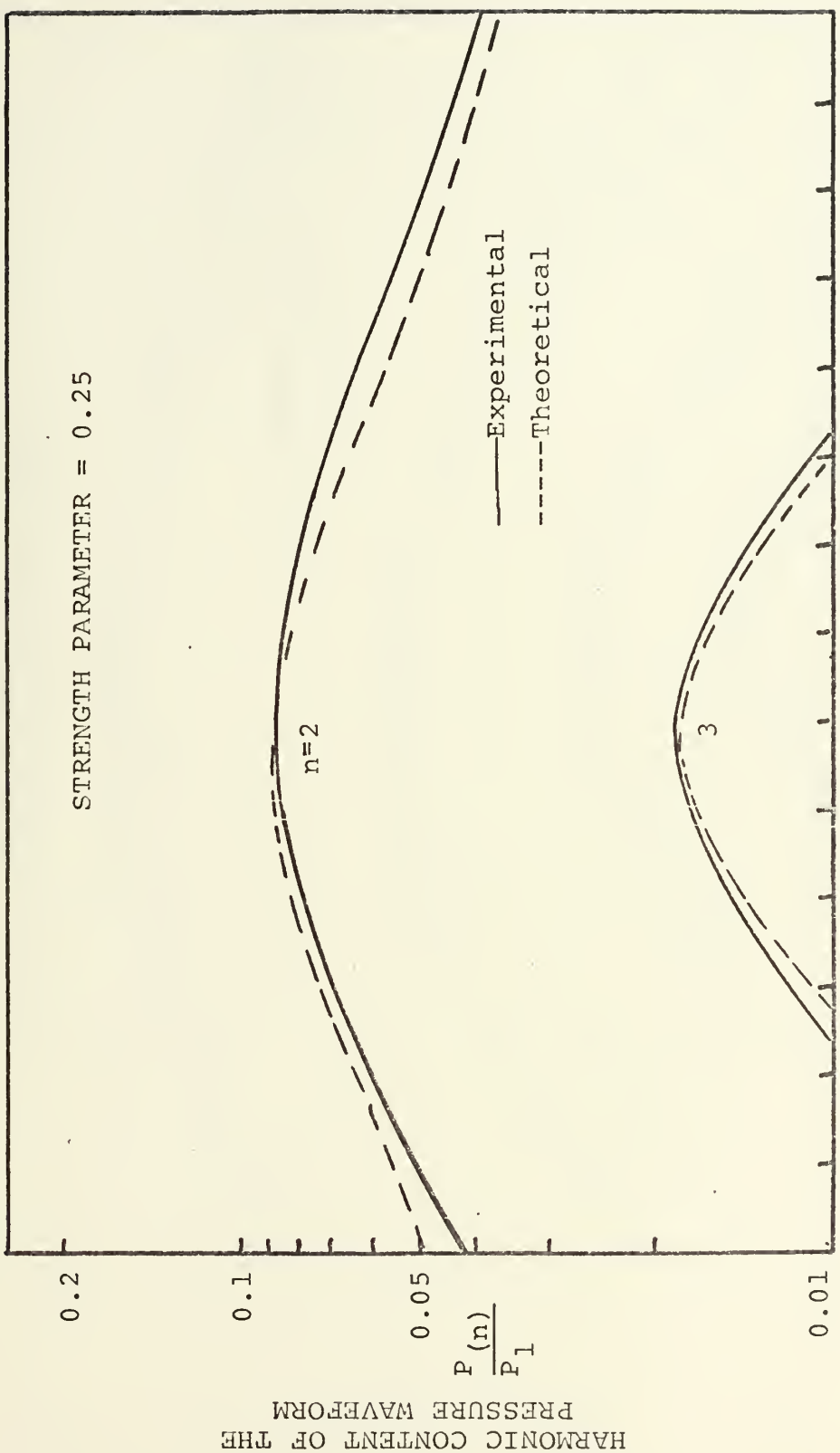


Figure 7. Harmonic Amplitudes SP = 0.25.

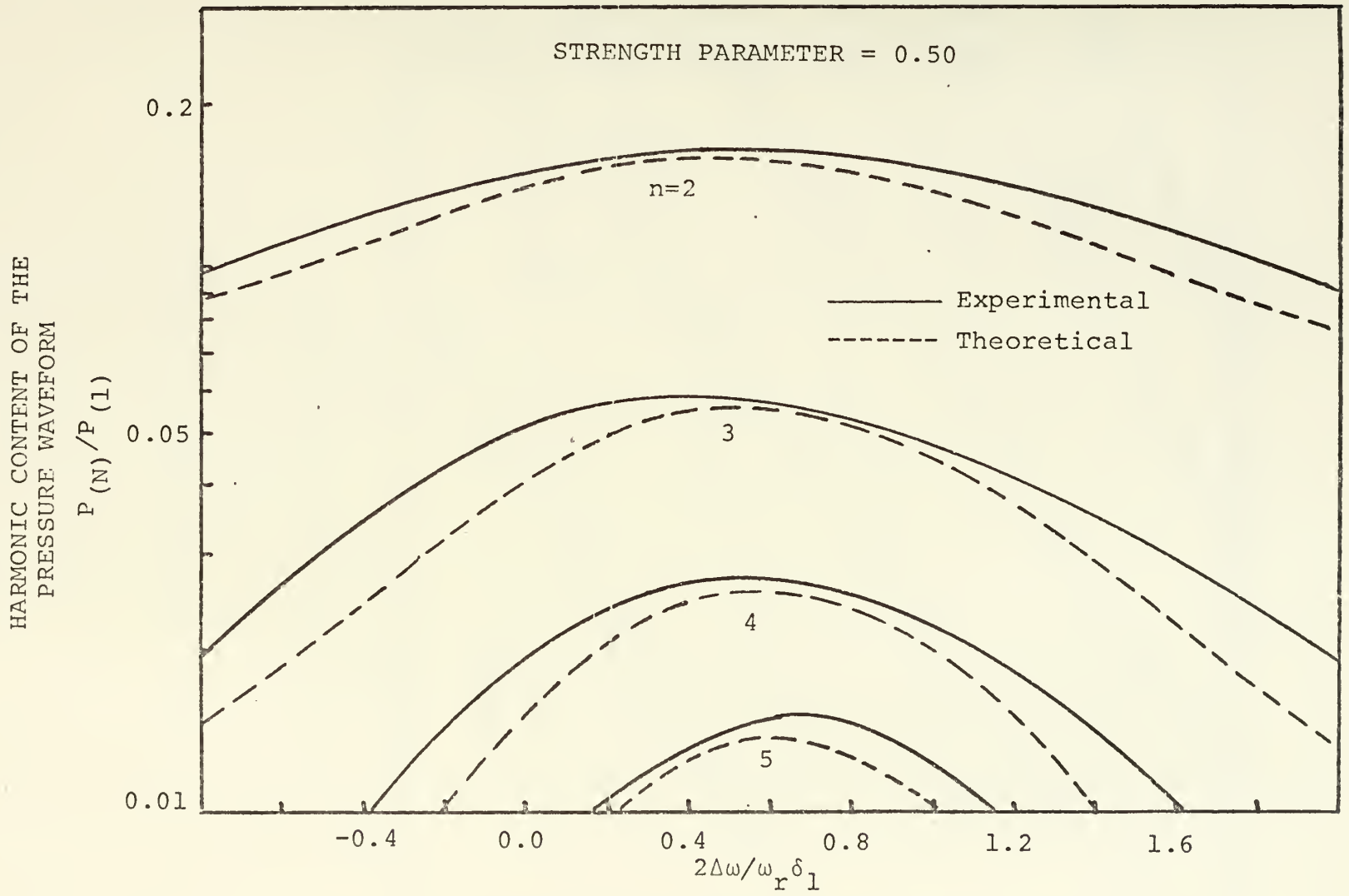


Figure 8. Harmonic Amplitudes SP = 0.50.

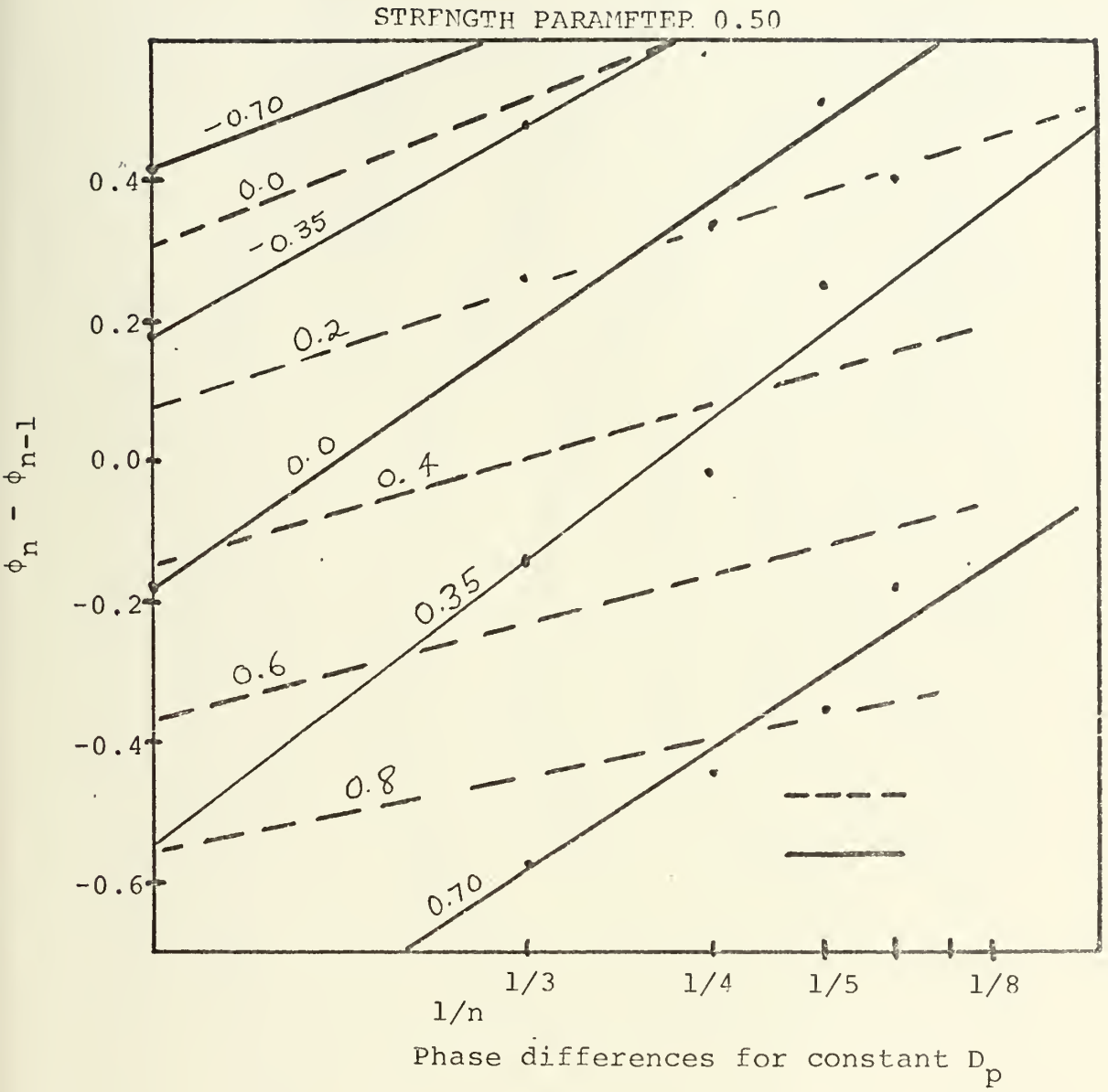


Figure 9. Phase Plot SP = 0.50.

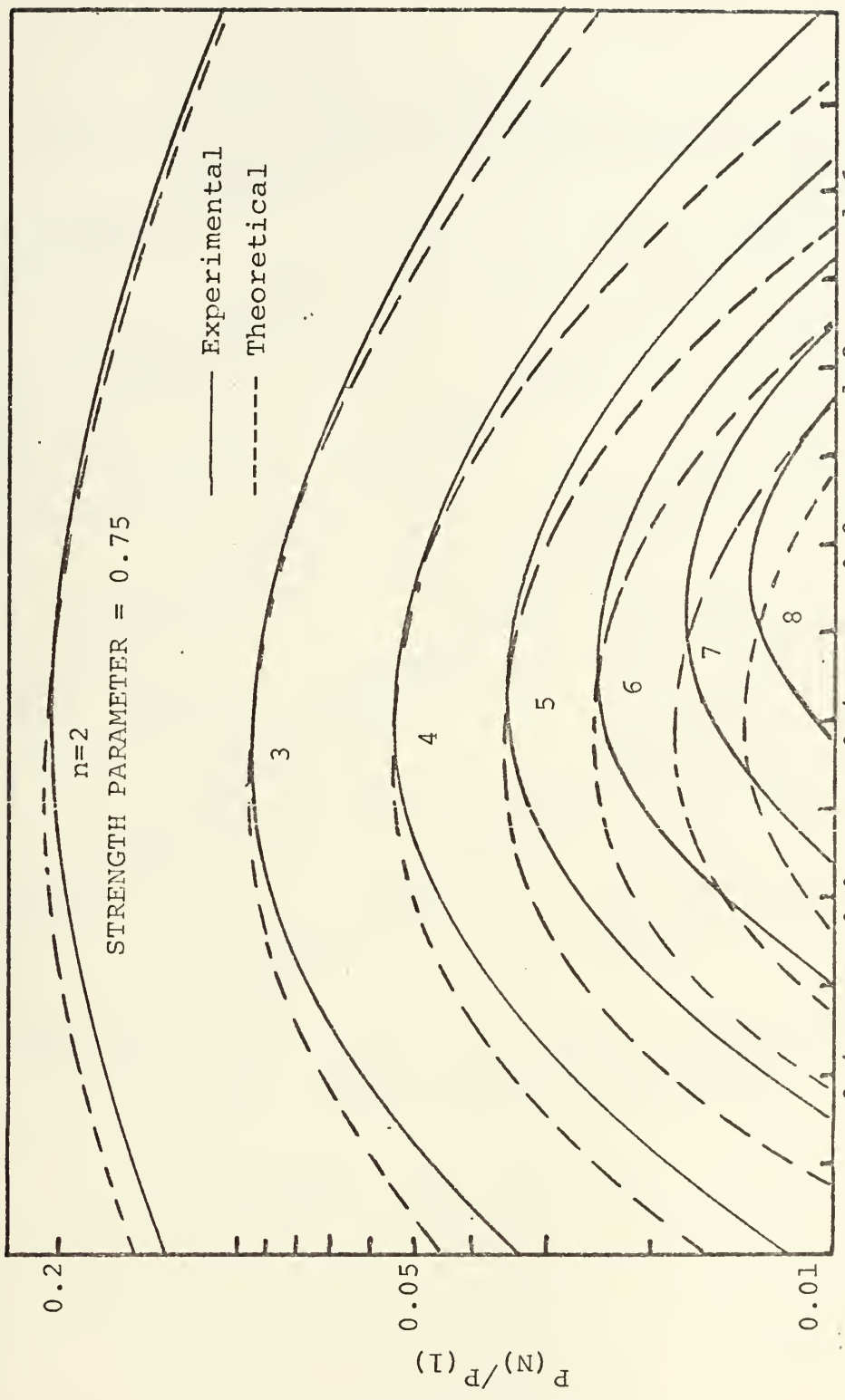
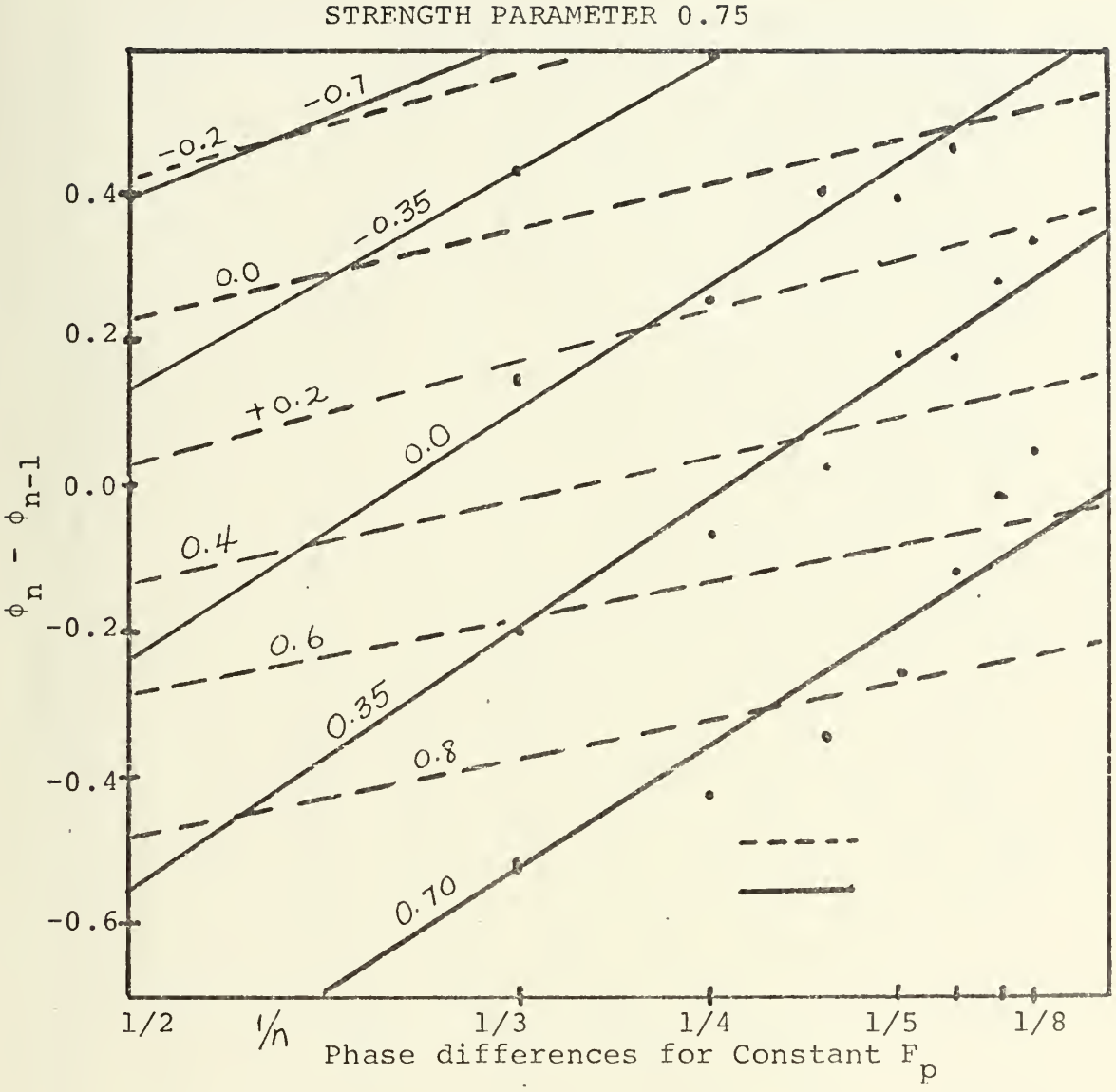


Figure 10. Harmonic Amplitudes SP = 0.75.



Figurell. Phase Plot SP = 0.75.

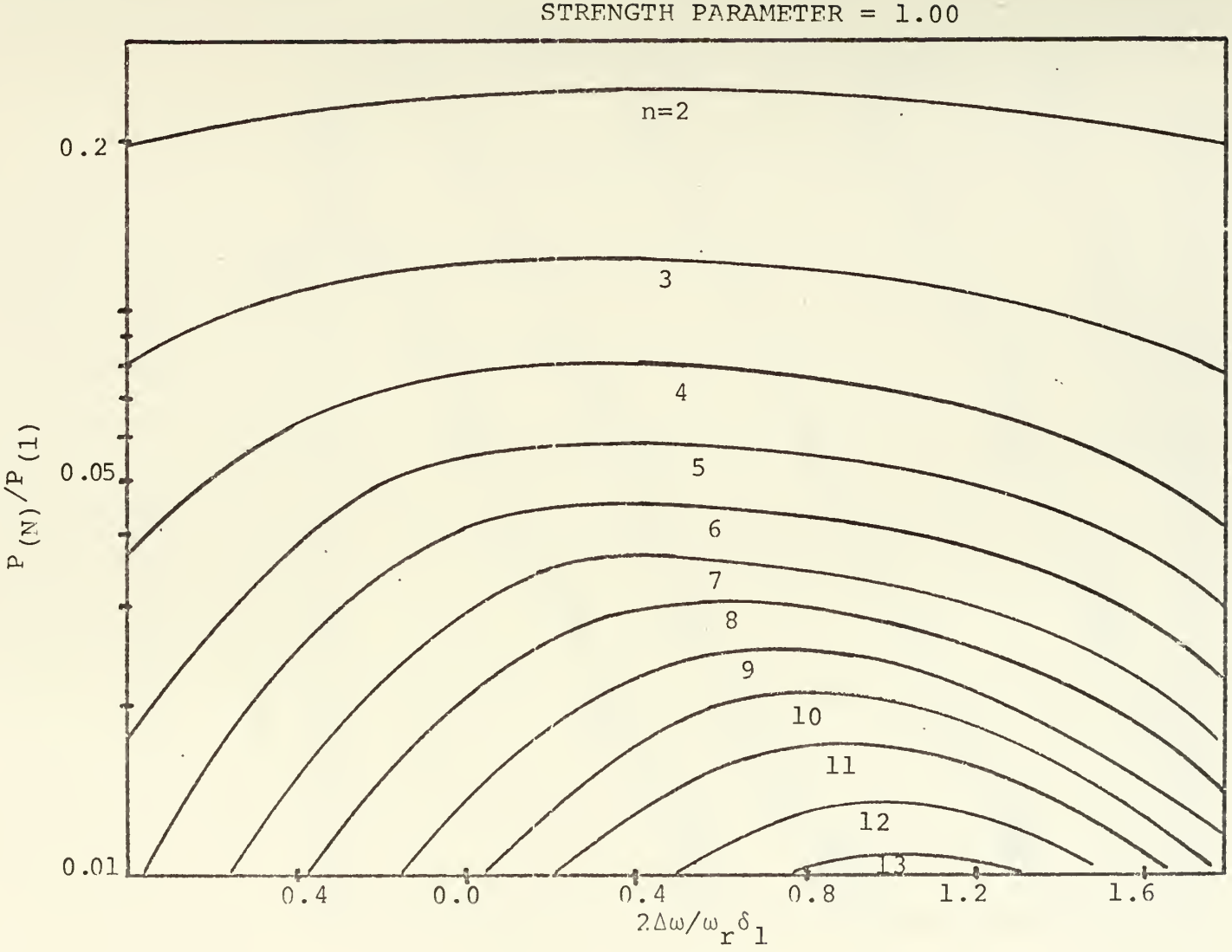


Figure 12. Harmonic Amplitudes SP = 1.00.

```
      CALL FORM(INDATA)                                                 WIN00440
C     PROCESS A NEW CHANNEL                                             WIN00450
   35 CONTINUE                                                          WIN00460
C     STEP THE CHANNEL COUNT                                            WIN00470
      K=K+1                                                             WIN00480
C     CONVERT THE DATA TO DECIMAL                                       WIN00490
      TSCALE=0.0                                                        WIN00500
      DSCALE=0.5                                                        WIN00510
      DO 4 I=1,NSAMP                                                    WIN00520
C     ZERO THE DATA VECTOR BEFORE ADDING THE RECORDS TOGETHER.          WIN00530
      IF(J.EQ.1) DATA(I,K)=0.0                                          WIN00540
      X(I)=INDATA(NC*(I-1)+K)*FACTOR                                    WIN00550
C     FIND THE NEGATIVE GOING AXIS CROSSING POINT                       WIN00560
      IF(ABS(X(I)).GT.DSCALE) GO TO 4                                   WIN00570
      IF(I.GT.10) GO TO 405                                             WIN00580
      DHP    =INDATA(NC*(I+8)+K)*FACTOR                                 WIN00590
      IF(DHP.GT.0.0) GO TO 4                                            WIN00600
      GO TO 404                                                         WIN00610
  405 DLP    =INDATA(NC*(I-9)+K)*FACTOR                                 WIN00620
      IF(DLP.LT.0.0) GO TO 4                                            WIN00630
  404 DSCALE=ABS(X(I))                                                  WIN00640
C     KEEP TRACK OF NEWI TO USE IN FINDING THE PHASE DIFFERENCE         WIN00650
C     BETWEEN CHANNELS.                                                 WIN00660
      NEWI=I                                                            WIN00670
    4 IF(ABS(X(I)).GT.TSCALE) TSCALE=ABS(X(I))                          WIN00680
      KNEW(K)=KNEW(K)+NEWI                                              WIN00690
C     REORGANIZE THE INPUT DATA SO THAT THE NEGATIVE GOING CROSSING     WIN00700
C     POINT IS THE FIRST DATA POINT.                                    WIN00710
      DO 44 I=1,NSAMP                                                   WIN00720
      IF(I.LT.NEWI) GO TO 444                                           WIN00730
      DATA(I-NEWI+1,K)=X(I)+DATA(I-NEWI+1,K)                            WIN00740
      GO TO 44                                                          WIN00750
  444 DATA(NSAMP-NEWI+1+I,K)=X(I)+DATA(NSAMP-NEWI+1+I,K)                WIN00760
   44 CONTINUE                                                          WIN00770
C     DETERMINE IF MORE RECORDS ARE TO BE READ BEFORE PROCESSING.       WIN00780
      IF(K.LT.NC) GO TO 35                                              WIN00790
      IF(J.LT.NREC) GO TO 1                                             WIN00800
C*****************************************************************     WIN00810
C                                                                       WIN00820
C     ONE CASE HAS BEEN READ IN TO THE DATA VECTOR AND IS READY TO      WIN00830
C     BE PROCESSED AT THIS POINT.                                       WIN00840
C                                                                       WIN00850
C*****************************************************************     WIN00860
C     ZERO THE CHANNEL COUNT                                            WIN00870
      K=0                                                               WIN00880
C     SET THE CHANNEL COUNT AND THE INITIAL SCALE AND EXTRACT THE DATA  WIN00890
C     FOR THE CURRENT CHANNEL NUMBER.                                   WIN00900
   53 K=K+1                                                             WIN00910
```

```
      SCALE=0.01                                                        WIN00920
      DO 55 I=1,NSAMP                                                   WIN00930
      Y(I)=DATA(I,K)                                                    WIN00940
   55 IF(DABS(Y(I)).GE.SCALE) SCALE=DABS(Y(I))                          WIN00950
C     LABEL THE CHANNEL NUMBER                                          WIN00960
      WRITE(6,45) NCASE,K                                               WIN00970
   45 FORMAT('1','CASE NUMBER',I3,6X,'CHANNEL NUMBER',I3,///)           WIN00980
C     FIND THE FOURIER COEFFICIENTS WITH SUBROUTINE FOX.                WIN00990
      CALL FOX(Y   ,NSAMP,NH,A,B,IER,SCALE)                             WIN01000
      WRITE(6,6)                                                        WIN01010
C     LABEL THE OUTPUT DATA                                             WIN01020
    6 FORMAT(1X,'HARMONIC',7X,'A(N)',10X,'B(N)',14X,'C(N)',10X,'PHI(N)',WIN01030
     1 10X,'A(N)/A(1)')                                                 WIN01040
      C(1)=A(1)                                                         WIN01050
C     CHANGE THE COEFFICIENTS TO THE FORM....A(N)SIN(NWT+PHI(N))        WIN01060
      DO 8 I=1,NH                                                       WIN01070
      IF(I.LT.2) GO TO 7                                                WIN01080
      C(I)=DSQRT(A(I)**2+B(I)**2)                                       WIN01090
      PHI=DATAN2(A(I),B(I))                                             WIN01100
    7 CONTINUE                                                          WIN01110
      IF(I.EQ.1) PHI=0.0                                                WIN01120
C     NUMBER THE HARMONICS                                              WIN01130
      N=I-1                                                             WIN01140
      RATIO=0.0                                                         WIN01150
      IF(I.EQ.1) GO TO 8                                                WIN01160
C     WRITE THE OUTPUT DATA                                             WIN01170
      RATIO=C(I)/C(2)                                                   WIN01180
    8 WRITE(6,9)(N,A(I),B(I),C(I),PHI,RATIO)                            WIN01190
    9 FORMAT(I4,5F16.4)                                                 WIN01200
C     FIND THE PHASE DIFFERENCE BETWEEN THE PRESSURE (CH1) AND THE      WIN01210
C     ACCELEROMETER(CH2)                                                WIN01220
      IF(K.EQ.2)DEL= IABS(KNEW(1)-KNEW(2))*360.0/(NREC*NSAMP)           WIN01230
C     DETERMINE THE NUMBER OF POINTS TO BE USED IN CALL DRAW SUBROUTINE WIN01240
      KK= 1+NSAMP/900                                                   WIN01250
      IF(NDRAW.EQ.0) KK=1                                               WIN01260
C     DETERMINE THE POINTS TO BE PLOTTED FROM THE ORIGINAL NORMALIZED,  WIN01270
C     SHIFTED DATA AND CREAT AN ADDITIONAL SET OF POINTS FROM           WIN01280
C     THE FOURIER COEFFICIENTS.                                         WIN01290
      L=1                                                               WIN01300
      SQ=0.0                                                            WIN01310
      Q=0.0                                                             WIN01320
      DO 95 I=1,NSAMP,KK                                                WIN01330
      DD=0.0                                                            WIN01340
      DO 97 KH=1,NH                                                     WIN01350
      THETA=(KH-1)*((I)*2.0*PI/FLOAT(NSAMP))                           WIN01360
   97 DD=DD+A(KH)*COS(THETA)+B(KH)*SIN(THETA)                           WIN01370
C     RECONSTRUCTED DATA ORDINATES, X AXIS POINTS, AND ORIGINAL         WIN01380
C     ORDINATES                                                         WIN01390
```

```
      C(L)=DD                                                          WIN01400
      X(L)=360.0*FLOAT(I-1)/FLOAT(NSAMP-1)                             WIN01410
      YY(L)=Y(I)/ SCALE                                                WIN01420
C     CALCULATE THE AVERAGE DIFFERENCE BETWEEN TNE INPUT POINTS AND    WIN01430
C     THE RECONSTRUCTED POINTS.  DO THE SAME FOR THE RMS ERROR.        WIN01440
      DELTA=C(L)-YY(L)                                                 WIN01450
      Q=DELTA+Q                                                        WIN01460
      SQ=DELTA**2+SQ                                                   WIN01470
C     DETERMINE THE NUMBER OF POINTS IN THE PLOTP SUBROUTINE           WIN01480
   95 L=L+1                                                            WIN01490
      AQ=Q/FLOAT(L-1)                                                  WIN01500
      RMS =SQRT(SQ/FLOAT(L-1))                                         WIN01510
      WRITE(6,950) AQ,RMS,FREQ,NSAMP                                   WIN01520
  950 FORMAT('0','AVERAGE DIFFERENCE',F10.6,//,' RMS ERROR',F7.4,//,   WIN01530
     2' FREQUENCY',F7.2,//,' NUMBER OF SAMPLES',I6)                    WIN01540
C     CORRECT THE NUMBER OF PLOT POINTS                                WIN01550
      L=L-1                                                            WIN01560
C                                                                      WIN01570
C     PLOT ON ONE GRAPH THE ORIGINAL DATA AND THE RECONSTRUCTED DATA   WIN01580
C     FOR EACH CHANNEL.                                                WIN01590
C     TO SCALE THE PLOTP ROUTINE SELECT TWO POINTS AND SET THEM        WIN01600
C     TO THE DESIRED EXTREMUM VALUES.                                  WIN01610
      NDRAW=0                                                          WIN01620
      IF(NDRAW.EQ.0) GO TO 91                                          WIN01630
      ITITLE(6)=SP                                                     WIN01640
      ITITLE(9)=FREQ                                                   WIN01650
      ITITLE(11)=NSAMP                                                 WIN01660
      CALL DRAW(L,X,YY,1,0,LABEL,ITITLE,60.0,0.4,3,0,2,2,6,6,1,LAST)   WIN01670
      CALL DRAW(L,X,C,3,0,LABEL,ITITLE,60.0,0.4,3,0,2,2,6,6,1,LAST)    WIN01680
   91 CONTINUE                                                         WIN01690
      YY(1)=1.2                                                        WIN01700
      YY(1+120*KK)=-1.2                                                WIN01710
      CALL PLOTP(X,YY,L,1)                                             WIN01720
      CALL PLOTP(X,C,L,3)                                              WIN01730
C                                                                      WIN01740
C                                                                      WIN01750
      IF(K.NE.2) GO TO 99                                              WIN01760
      WRITE(6,98) SP,DEL                                               WIN01770
   98 FORMAT('0','STRENGTH PARAMETER=',F6.3,'PHASE=',F7.2)             WIN01780
C     CHECK THE CHANNEL NUMBER AND DETERMINE IF ANOTHER CHANNEL IS     WIN01790
C     TO BE PROCESSED OR A NEW CASE IS TO BE READ.                     WIN01800
   99 CONTINUE                                                         WIN01810
      IF(K.EQ.NC) GO TO 111                                            WIN01820
      GO TO 53                                                         WIN01830
   10 WRITE(6,11) J                                                    WIN01840
   11 FORMAT ('0',5X,'READ ERROR, RECORD NO.',I3)                      WIN01850
      GO TO  1                                                         WIN01860
   12 WRITE(6,13) J                                                    WIN01870
```

```
 13 FORMAT ('0',5X,'END OF TAPE, RECORD NO.=',I3)                    WIN01880
 14 CONTINUE                                                         WIN01890
    STOP                                                             WIN01900
    END                                                              WIN01910

    SUBROUTINE FOX(FNT , NSAMP,M,A,B,IER,SCALE)                      WIN01920
    IMPLICIT REAL*8(A-H),REAL*8(O-Z)                                 WIN01930
    DIMENSION A(1),B(1),FNT(1)                                       WIN01940
    IER=0                                                            WIN01950
    N=(NSAMP-1)/2                                                    WIN01960
 20 IF(M) 30,40,40                                                   WIN01970
 30 IER=2                                                            WIN01980
    RETURN                                                           WIN01990
 40 IF(M-N) 60,60,50                                                 WIN02000
 50 IER=1                                                            WIN02010
    RETURN                                                           WIN02020
 60 AN=N                                                             WIN02030
    MP1 = M+1                                                        WIN02040
    DZ = 0.D0                                                        WIN02050
    D1 = 1.D0                                                        WIN02060
    D2 = 2.D0                                                        WIN02070
    COEF = D2/(D2 * AN + D1)                                         WIN02080
    CONST = 3.141592653589793 * COEF                                 WIN02090
    S1 =  DSIN(CONST)                                                WIN02100
    C1 =  DCOS(CONST)                                                WIN02110
    C = D1                                                           WIN02120
    S = DZ                                                           WIN02130
    J=1                                                              WIN02140
    FNTZ=FNT(1)/SCALE                                                WIN02150
 70 U2 = DZ                                                          WIN02160
    U1 = DZ                                                          WIN02170
    I=2*N+1                                                          WIN02180
 75 U0=FNT(I)/SCALE+D2*C*U1-U2                                       WIN02190
    U2=U1                                                            WIN02200
    U1=U0                                                            WIN02210
    I=I-1                                                            WIN02220
    IF(I-1) 80,80,75                                                 WIN02230
 80 A(J)=COEF*(FNTZ+C*U1-U2)                                         WIN02240
    B(J)=COEF*S*U1                                                   WIN02250
    IF(J-(M+1)) 90,100,100                                           WIN02260
 90 Q=C1*C-S1*S                                                      WIN02270
    S=C1*S+S1*C                                                      WIN02280
    C=Q                                                              WIN02290
    J=J+1                                                            WIN02300
    GO TO 70                                                         WIN02310
100 A(1) = A(1) / D2                                                 WIN02320
    RETURN                                                           WIN02330
```

```
         END                                                              WIN02340
//ASM.SYSIN  DD  *                                                        WIN02360
FORM     START 0                                                          WIN02370
         STM   14,12,12(13)                                               WIN02380
         BALR  6,0                                                        WIN02390
         USING *,6                                                        WIN02400
         USING DATA,7                                                     WIN02410
         SR    7,7                                                        WIN02420
         L     11,=F'1090'                                                WIN02430
         L     12,0(1)                                                    WIN02440
LOOP     L     2,NUM(12)                                                  WIN02450
         LR    3,7                                                        WIN02460
         SRDL  2,6                                                        WIN02470
         SRL   2,2                                                        WIN02480
         SRDL  2,6                                                        WIN02490
         SRL   2,2                                                        WIN02500
         SRDL  2,6                                                        WIN02510
         SRL   2,2                                                        WIN02520
         SRDL  2,6                                                        WIN02530
         ST    3,NUM(12)                                                  WIN02540
         LA    12,4(12)                                                   WIN02550
         BCT   11,LOOP                                                    WIN02560
         LM    2,12,28(13)                                                WIN02570
         MVI   12(13),X'FF'                                               WIN02580
         BCR   15,14                                                      WIN02590
DATA     DSECT                                                            WIN02600
NUM      DS    1F                                                         WIN02610
         END                                                              WIN02620
//GO.FT02F001 DD UNIT=OCO,VOL=SER=WINN,LABEL=(6,NL),                      WIN02640
//       DISP=(OLD,KEEP),DCB=(DEN=1,RECFM=F,BLKSIZE=4360)                 WIN02650
//GO.SYSIN  DD *                                                          WIN02660
J.R. WINN 1542   STRENGTH PARAMETER=                                      WIN02670
FREQUENCY=                                     SAMPLES                    WIN02680
1063 94.1                                                                 WIN02690
1063 94.1                                                                 WIN02700
1063 94.1                                                                 WIN02710
1055 94.8                                                                 WIN02720
1055 94.8                                                                 WIN02730
1055 94.8                                                                 WIN02740
1065 93.9                                                                 WIN02750
1065 93.9                                                                 WIN02760
1065 93.9                                                                 WIN02770
1051 95.2                                                                 WIN02780
1051 95.2                                                                 WIN02790
1051 95.2                                                                 WIN02800
1059 94.5                                                                 WIN02810
1059 94.5                                                                 WIN02820
1059 94.5                                                                 WIN02830
```

B. ANALOG CONVERSION

```
      DIMENSION IBUF(2048,2), LOCB(-1'1), MAXBS(-1'1)                    003
      INTEGER RECNUM                                                     004
      NAMELIST NREC, NSAMP, NCHAN, ITAPE,NDEL                            005
1     INPUT(101)                                                         006
      LOCB(-1)=LOCF(IBUF(1,1))                                           007
      LOCB(1)=LOCF(IBUF(1,2))                                            008
      NWORDS=NSAMP*NCHAN                                                 009
      MAXBS(-1)=LOCB(-1)+NWORDS-1                                        010
      MAXBS(1)=LOCB(1)+NWORDS-1                                          011
      IF(SENSE SWITCH 6)2,15                                             012
2     NB=1                                                               013
      IND=0                                                              014
      RECNUM=0                                                           015
      NEWBUF=LOCB(1)                                                     016
      MAXB=MAXBS(-1)                                                     017
      CALL ADSTART(NCHAN,LOCB(-1),NEWBUF,MAXB,RECNUM,11S)                018
      MAXB=MAXBS(1)                                                      019
3     IF(TEST(1).GT.0)GO TO 3                                            020
      CALL ENABLE                                                        021
5     CONTINUE                                                           022
10    GO TO 5                                                            023
11    IF(IND.EQ.1)GO TO 90                                               024
      IF(TEST(1).GT.0.OR.RECNUM.GE.NREC)CALL DISABLE                     025
      NB=-NB                                                             026
      NEWBUF=LOCB(NB)                                                    027
      MAXB=MAXBS(NB)                                                     028
      IND=1                                                              029
      CALL BUFFEROUT(ITAPE,1,IBUF(1,(3+NB)/2),NWORDS,IND)                030
      IF(TEST(1).LT.0.AND.RECNUM.LT.NREC)GO TO 5                         031
      CALL ADSTOP                                                        032
X     CALL PROCESS(IBUF,NSAMP,NCHAN,2S)                                  033
      OUTPUT(101)RECNUM                                                  034
15    OUTPUT(101)-OPTION=(I1)-                                           035
      READ(101,100)NOPT                                                  036
100   FORMAT(I1)                                                         037
      GO TO(1,2,30,40,50,60,70)NOPT                                      038
30    ENDFILE(ITAPE)                                                     039
      OUTPUT(101)-EOF-                                                   040
      GO TO 15                                                           041
40    REWIND(ITAPE)                                                      042
      GO TO 15                                                           043
50    OUTPUT(101)-SKIPFILES=(I4)-                                        044
      READ(101,101)NF                                                    045
101   FORMAT(I4)                                                         046
      DO 55 I=1,NF                                                       047
51    CALL BUFFERIN(ITAPE,1,IBUF(1,1),1,IND)                             048
52    IF(IND.LT.2)GO TO 52                                               049
      IF(IND.NE.3)GO TO 51                                               050
```

```
55    CONTINUE                                                          051
      OUTPUT(101)NF                                                     052
      GO TO 15                                                          053
60    OUTPUT(101)-NUMWORDS TO LIST=(I4)-                                054
      READ(101,101)NW                                                   055
      WRITE(101,105)NW,NCHAN                                            056
105   FORMAT(- WRITE - I4 - WORDS, - I2 - AT A TIME-)                   057
      IND=1                                                             058
      CALL BUFFERIN(ITAPE,1,IBUF(1,1),NWORDS,IND)                       059
66    IF(IND.EQ.1)GO TO 66                                              060
62    GO TO(62,63,64,65)IND                                             061
63     WRITE(6,102)                                                     062
102   FORMAT(1H1)                                                       063
      DO 631 I=1,NW,NCHAN                                               064
      WRITE(6,104)(IBUF(J,1),J=I,I+NCHAN-1)                             065
104    FORMAT(12010)                                                    066
631   CONTINUE                                                          067
      GO TO 15                                                          068
64     OUTPUT(101)-EOF READ-                                            069
      GO TO 15                                                          070
65     OUTPUT(101)-READ ERR-                                            071
      GO TO 63                                                          072
70    OUTPUT(101)-START ANALOG RECORDER-                                073
      OUTPUT(101)-TYPE * C/R TO CONTINUE-                               074
      INPUT(101)                                                        075
      IND=1                                                             076
      CALL BUFFERIN(ITAPE,1,IBUF,NWORDS,IND)                            077
76    IF(IND.EQ.1)GO TO 76                                              078
71    GO TO(71,72,64,74)IND                                             079
72    DO 73 I=1,NWORDS                                                  080
73    IBUF(I,1)=IBUF(I,1)/2**10                                         081
      DO 75 I=1,NWORDS,NCHAN                                            082
      DO 75 J=1,NCHAN                                                   083
      CALL DAC(J,IBUF(I+J-1,1))                                         084
      N=NDEL                                                            085
      CALL DELAY                                                        086
75    CONTINUE                                                          087
      GO TO 15                                                          088
74    OUTPUT(101)-READ ERROR-                                           089
      GO TO 72                                                          090
90    CALL DISABLE                                                      091
      CALL ADSTOP                                                       092
      OUTPUT(101)-RATE ERR-,RECNUM                                      093
      GO TO 15                                                          094
      END                                                               095
```

```
      SUBROUTINE PROCESS(IB,NS,NC,IS)                                   096
      DIMENSION IB(NC,NS),MEAN(10),SIGMA(10)                            097
      REAL MEAN                                                         098
      SCALE=100./2**23                                                  099
      DO 1 I=1,10                                                       100
1     SIGMA(I)=MEAN(I)=0.                                               101
      DO 100 I=1,NC                                                     102
      DO 10 J=1,NS                                                      103
10    MEAN(I)=MEAN(I)+SCALE*IB(I,J)                                     104
      MEAN(I)=MEAN(I)/NS                                                105
      DO 20 J=1,NS                                                      106
20    SIGMA(I)=SIGMA(I)+(MEAN(I)-IB(I,J)*SCALE)**2                      107
      SIGMA(I)=SQRT(SIGMA(I)/NS)                                        108
      WRITE(6,1000)I,MEAN(I),SIGMA(I)                                   109
1000  FORMAT($ CHAN $I2$  MEAN=$F8.4$  SIGMA=$F8.4/)                    110
100   CONTINUE                                                          111
30    IF(TEST(1).LT.0)GO TO 30                                          112
      IF(TEST(2).GT.0)RETURN                                            113
      RETURN IS                                                         114
      END                                                               115
¬META9200 SI,LO,GO                                                      116
$ADSTART PZE                                                            117
         BRM      9SETUPN                                              118
         PZE      6                                                    119
NCH      PZE                                                           120
BUF      PZE                                                           121
NEWBUF   PZE                                                           122
MAXB     PZE                                                           123
RECNUM   PZE                                                           124
NEXLOC   PZE                                                           125
         LDA      ENDBRM                                               126
         XMA      040                                                  127
         STA      SV040                                                128
         LDA      INTBRM                                               129
         XMA      052                                                  130
         STA      SV052                                                131
         LDA      *NCH                                                 132
         STA      INCR                                                 133
         ADD      =COMM                                                134
         COPY     (5,1)                                                135
         STA      COMLOC                                               136
         LDA      *NCH                                                 137
         LLSA     15                                                   138
         ADD      =COMM                                                139
         STA      0,1                                                  140
         STA      CONTR                                                141
         LDA      *BUF                                                 142
         STA      COMM                                                 143
```

```
         LDA    *MAXB
         STA    MAX
          SKR    NFULL
          BRU    $-1
          EOM    034001
          POT    CONTR
          BRR    ADSTART
INTBRM    BRM    ADFAST
ENDBRM    BRM    ENDAD
SVC40     PZE
ENDAD     PZE
          DIR
          HLT
          EOM    034001
          POT    CONTR
          EIR
          BRC    *ENDAD
$ADSTOP   PZE
          LDA    SVC40
          STA    C40
          LDA    SV052
          STA    052
          STZ    *COMLOC
          MPO    ADSTOP
          BRR    ADSTOP
COMLOC    PZE
$ADFAST   PZE
          DIR
          STD    SVAB
          SKN    NFULL
          BRU    NXTBUF
          LDP    INCR
          ADD    COMM
          STA    COMM
          ADD    INCR
         SKL    MAX
          STB    NFULL
          LDP    SVAB
          EIR
          BRC    *ADFAST
NXTBUF    LDA   *NEWBUF
          STA    COMM
          LDA   *MAXB
          STA    MAX
          SKR    NFULL
          BRU    $-1
          MPO   *RECNUM
          LDP    SVAB
```

```
            EIR
            BRC     *NEXLOC
COMM        RES     33
CONTR       PZE
MAX         PZE
SVAR        RES     2
INCR.       DATA    6,0
NFULL       PZE
SV052       PZE
            END
```

BIBLIOGRAPHY

1. A. B. Coppens and J.V. Sanders, "Finite-amplitude Standing Waves in Rigid-walled Tubes," J.Acoust. Sec. Am., V. 43, P. 516-529, March 1968.

2. A. B. Coppens and J. V. Sanders, Finite-amplitude Acoustic Processes in Ducts, paper presented at Applied Research Laboratories Conference, 5th, Austin, Texas, 10 November 1969.

3. Beech, W. L., Finite-amplitude Standing Waves in Rigid-Walled Tubes, M.S. Thesis, Naval Postgraduate School, Monterey, Calif., 1967.

4. G. Goertzel, "An Algorithm for the Evaluation of Finite Trigonometric Series," Amer. Math. Monthly, V. 65, P. 34-35, January 1958.

5. J. W. Cooley and J. W. Tukey, "An Algorithm for the Machine Calculation of Complex Fourier Series," Mathematics of Computations, V. 19, P. 297-303, April 1965.

6. Naval Postgraduate School Computer Facility Technical Note 0211-04, Procedures for Electrical Engineering Computer Laboratory Tapes and Fleet Numerical Weather Central Tapes, by P.C. Zeleny and R.D. Brunell, P. 1-5, April 1969.

7. Naval Postgraduate School Computer Facility Technical Note 0211-08, Procedures for Converting 7-Track Magnetic Tape to 9-Track Magnetic Tape, by S.D. Raney, P. 1-11, June 1970.

8. A. B. Coppens, personal communication.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	2
2.	Library, Code 0212 Naval Postgraduate School Monterey, California 93940	2
3.	Assoc. Professor James V. Sanders, Code 61Sd Department of Physics Naval Postgraduate School Monterey, California 93940	4
4.	Assoc. Professor Alan B. Coppens, Code 61Cz Department of Physics Naval Postgraduate School Monterey, California 93940	1
5.	James R. Winn 5050 Gola Dr. Wooster, Ohio 44691	1

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

Naval Postgraduate School
Monterey, California 93940

2a. REPORT SECURITY CLASSIFICATION

Unclassified

2b. GROUP

3. REPORT TITLE

FOURIER ANALYSIS OF EXPERIMENTAL FINITE-AMPLITUDE STANDING WAVES

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Master's Thesis; June 1971

5. AUTHOR(S) (First name, middle initial, last name)

James Richard Winn, Lieutenant, United States Navy

6. REPORT DATE

June 1971

7a. TOTAL NO. OF PAGES

53

7b. NO. OF REFS

8

8a. CONTRACT OR GRANT NO

b. PROJECT NO

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Naval Postgraduate School
Monterey, California 93940

13. ABSTRACT

Finite-amplitude standing waves in air at ambient conditions contained in a rigid-walled cylindrical tube with a large length-to-diameter ratio were experimentally investigated. The pressure waveform at the end of the tube was digitized and Fourier analyzed on an IBM 360 digital computer. Amplitudes and phases were obtained for all harmonics with amplitudes greater than 1% of the fundamental for strength parameters from 0.25 to 1.00 and for frequency parameters from -0.8 to 2.0. The strength and frequency parameters are defined as MbQ and $2\Delta f/\Delta f$ respectively, where M is the Mach number of fundamental, b the nonliniarity parameter, Q the quality factor of the resonator, Δf the frequency away from fundamental resonance, and Δf the band width at the half-power points. When these results are compared to the theoretical model of Coppens and Sanders, it is seen that while the theory accurately predicts the magnitude and shape of the harmonic content, it consistently underestimates the frequency at which each harmonic peaks. In addition, the theory fails to predict, except qualitatively, the phase angles.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6811

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Finite-amplitude standing waves						
Strength parameter						
Frequency parameter						

14 AUG 78

128443

Thesis
W6475
c.1

Winn

Fourier analysis of experimental finite-amplitude standing waves.

14 AUG 78

Thesis
W6475
c.1

Winn

128443

Fourier analysis of experimental finite-amplitude standing waves.

thesW6475
Fourier analysis of experimental finite-
3 2768 001 89985 9
DUDLEY KNOX LIBRARY